PROCESS FOR WRITING BRAGG GRATINGS, APPARATUS FOR THE USE OF THIS PROCESS AND BRAGG GRATING DEVICES OBTAINED BY THIS PROCESS

Technical field

This invention relates to a process for writing Bragg gratings, and an apparatus for the use of this process.

It applies to obtaining a large number of Bragg grating devices and in particular to the manufacture of phase skip Bragg gratings with high spectral selectivity, overwriting of one Bragg grating to erase it and replace it with another, the manufacture of Fabry-Perot cavities and the manufacture of Bragg gratings with a predefined index modulation envelope, both for optical fibers and for integrated optical guides.

State of prior art

Bragg gratings were first used in optical fibers about twenty years ago. Before this time, these components were frequently used in the field of integrated optics, acousto-optics and in semi-conductors, for example in distributed Bragg reflector lasers.

A conventional Bragg grating behaves like a spectral filter with regard to the wave that passes through it. It reflects a band of wavelengths with a given width (typically a few hundred picometers) around a central resonance value λB called the Bragg wavelength. In transmission, by complementarity, the

spectrum of the guided wave loses this same band of wavelengths (see Figure 1 on which the variations of the transmission T of a conventional Bragg grating are represented as a function of the wavelength, where λB = 1319 nm).

There are many applications for Bragg gratings, mainly for telecommunications (for example for multiplexing, demultiplexing, add-drop devices, distributed feed back lasers). Bragg gratings made from optical fibers also revolutionized the field of optical fiber sensors due to their role as transducers (for example for temperatures and elongations).

Conventional Bragg gratings are known formed by a simple sinusoidal modulation, for which the spectral response is given in Figure 1, and advanced Bragg gratings on which the sinusoidal modulation is modified to enable the creation of filters with particular spectral shapes; it is thus possible to improve conventional Bragg gratings depending on the field of application considered or needs, or even to make new components.

In practice, the production of an advanced Bragg grating requires a process and an apparatus with a number of qualities. The following problems need to be solved:

- the apparatus must be capable of producing a Bragg grating conform with the required theoretical result,
- the manufacturing process used with the apparatus must provide access to a number of parameters involved in making Bragg gratings,

- writing two Bragg gratings twice in succession using the same protocol must give the same result,
- the process and the apparatus must be simple and must be useable by anyone working in this field to obtain the required Bragg grating, and
- if it is to be marketable, the apparatus must be inexpensive and must be useable to make various families of Bragg gratings at an inexpensive price.

Description of the invention

This invention is designed to solve the above problems.

The first objective of the invention is an process for writing a Bragg grating in a transparent substrate forming a light guide, particularly in an optical fiber, the Bragg grating forming a spectral filter with regard to a light wave that passes through it, process according to which the interference pattern between two light beams with the same wavelength and coherent with each other but with an angular offset, is transferred directly into the substrate due to a photosensitivity phenomenon within the same said substrate, this interference pattern being transferred in the substrate in the form of a modulation of the refraction index of this substrate, this process being characterized in that at least one of the said light beams is divided into at least two sub-beams offset in phase with respect to each other.

According to a first particular embodiment of the process according to the invention, the interference pattern is transferred according to an amplitude separation configuration.

According to a second particular embodiment, the interference pattern is transferred according to a wave front separation configuration.

In the invention, the position of the phase shift or the value of this phase shift or the position and value of this phase shift in the light beam formed by the two sub-beams, can be modified with time.

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The invention also applies to an apparatus for use of the process according to the invention, this apparatus being characterized in that it comprises:

- at least one phase splitter capable of creating a phase shift between at least two sub-beams, due to a difference in the optical path, and
- a means of adjusting the position of the phase splitter, this adjustment means having at least two degrees of freedom, one being angular degree of freedom provided for adjustment of the value of the phase shift, and the other being a translation degree of freedom provided for adjustment of the position of the phase shift in the light beam formed by the two sub-beams.

The composition of the apparatus according to the invention is very simple, it is easy to adjust and use, and it is very flexible in use.

According to a first particular embodiment of the apparatus according to the invention, this apparatus also comprises interferometric means with two or three

mirrors for transferring the interference pattern according to an amplitude separation configuration.

According to a second particular embodiment, this apparatus also comprises interferometric means with a prism or a Lloyd folded mirror for transferring the interference pattern according to a wave front separation configuration.

The invention also relates to:

- a phase skip Bragg grating with high spectral selectivity obtained by the process according to the invention, the phase shift between the two sub-beams advantageously being equal to π,
- a Bragg grating obtained by the process according to the invention, this Bragg grating being identical to a pre-written Bragg grating and being written on this pre-written grating, at the same position, with a phase change of π over the entire length of the pre-written grating, to erase all or some of the original grating in order to obtain a given reflection coefficient,
- a Fabry-Perot cavity delimited by two Bragg gratings at different positions in space, these two Bragg gratings being obtained by the process defined in the invention,
- a Bragg grating with a determined index modulation envelope, particularly an apodized Bragg grating, obtained by the process according to the invention, by successively writing two Bragg gratings comprising parts in phase opposition, the time taken to overwrite one

Bragg grating by the other being variable, to give a variable phase shift and a variable value of the phase shift, for example the position of the phase shift being displaced by a programmable movement.

Brief description of the drawings

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This invention will be better understood after reading the following example embodiments given for information only and in no way restrictive, with reference to the attached drawings in which:

- Figure 1, described above, describes transmission variations in a conventional Bragg grating as a function of the wavelength,
- Figure 2 diagrammatically illustrates the interference diagram for two plane waves with no phase splitter,
- Figure 3 diagrammatically illustrates the interference diagram for two plane waves in the presence of a phase splitter,
- Figure 4 diagrammatically illustrates phase splitters placed in series,
- Figure 5 diagrammatically illustrates a curved phase splitter,
- Figure 6 diagrammatically illustrates a phase splitter formed by a lens,
- Figure 7 diagrammatically illustrates a phase splitter with an index change,
- Figure 8 diagrammatically illustrates a phase splitter inclined with respect to an incident light beam,

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- Figure 9 diagrammatically illustrates a support device for a phase splitter that could be used in the invention,
- Figure 10 diagrammatically illustrates an amplitude separation writing process for a phase skip Bragg grating according to the invention, for an assembly with transverse irradiation,
- Figure 11 diagrammatically illustrates a wave front separation writing process for a phase skip Bragg grating according to the invention, using the prism method,
- Figure 12 diagrammatically illustrates another wave front separation writing process for a phase skip Bragg grating according to the invention, using a Lloyd mirror,
- Figure 13 shows variations in the transmission of a phase skip Bragg grating as a function of the wavelength,
- Figure 14 diagrammatically illustrates a partial double reflection in a Bragg grating around a phase change due to a cavity,
- Figure 15 diagrammatically illustrates propagative and counter-propagative coupling in a phase skip Bragg grating,
- Figure 16 diagrammatically illustrates an example of an index modulation with linear envelope, and
- Figure 17 diagrammatically illustrates an example of an index modulation apodized by a Gaussian curve.

Detailed description of particular embodiments

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According to this invention, interference is generated with one or a plurality of phase sifts by means of one or a plurality of optical phase shifting elements or phase splitters.

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The first step (Figure 2) is the simple case of two plane light waves O_1 and O_2, output from the same light beam and with no phase splitter. The electrical fields for these two waves are denoted $\vec{E}_1$ and $\vec{E}_2$, the corresponding wave planes are denoted P_1 and P_2 and the corresponding wave vectors are denoted $\vec{k}_1$ and $\vec{k}_2$. The modulus of $\vec{k}_1$ and $\vec{k}_2$ is denoted k, and the modulus of $\vec{E}_1$ and $\vec{E}_2$ is denoted ξ_o. The intensity I(z) resulting from the interference of these two waves on the Oz axis in Figure 2 is therefore in the form:

$$I(z) = 2\xi_o^2 . [1+\cos(2k \sin(\Psi).z)]$$

The period of the modulation thus created depends on the angle Ψ between the wave vectors $\vec{k}_1$ and $\vec{k}_2$ and the axis of observation OZ of the interference fringes.

The sequence of dark and light fringes can be transferred in a wave guide by a photosensitive phenomenon, the efficiency of which depends on many parameters, for example such as the type of material used in the guide, the power of the writing beams, and the exposure time. Thus a Bragg grating can be written in the guide.

We will now consider interference between these two waves when a phase 2 splitter is located on the path of the wave O_2 parallel to the plane of wave P_2 according to the invention. We will use the same

notation as above, considering the effect of the splitter on $\vec{E}_2$ (Figure 3).

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Two zones I and II corresponding to two parallel sub-beams formed by the wave O_2 after it has passed through the splitter 2, which is thicker in the part facing area II than in the part facing area I. The intensity I(z) then becomes:

$$I(z) = 2\xi_o^2 . \ (1 + \cos(2k \sin(\Psi).z)) \text{ for } 0 < z < z_t$$

$$I(z) = 2\xi_o^2 . \ (1 + \cos(2k \sin(\Psi).z+\Delta\Phi) \text{ for } z_t < z < z_f$$

The phase change or shift $\Delta\Phi$ introduced by the phase splitter in one of the two beams associated with the waves then takes place in the intensity modulation that will generate the Bragg grating.

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On Oz, the phase change abscissa is determined by the relative position of the splitter 2 with respect to beam O_2. Therefore, this abscissa z_t can be modified very easily by the splitter translating along a y axis parallel to this splitter. It can be seen that the interference area is delimited by the abscissas O and z_f on the Oz axis.

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The value $\Delta\Phi$ is determined by the difference in optical path in the splitter between areas I and II. This splitter can be made such that $\Delta\Phi = \pi$. Furthermore, this value can be modified very simply by rotating the splitter at an angle θ to incline this splitter with respect to beam O_2.

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According to the invention, two waves with multiple phase changes can also be made to interfere; in the same way as a phase splitter comprising a step

induces a phase shift in the interference pattern as shown in Figure 3, a series of splitters 4, 6, 8 placed in sequence can be placed in one O_3 of the two interfering beams (for example ultraviolet beams) (Figure 4). The result is then an interference pattern with a series of phase changes corresponding to steps 10, 12, 14 in splitters 4, 6, 8 respectively.

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Another solution is to combine this series of splitters into a single splitter that induces a series of phase shifts by multiple changes in the optical path (stepped splitter).

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We will now explain the production of a phase splitter. The material from which this splitter is made must be transparent to the wavelength(s) that will be used to write the Bragg grating by photosensitivity in a light guide.

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In the following, the production of a single phase change splitter is described, but splitters with several phase changes could be made in a similar manner.

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The splitter, or the element creating the optical phase shift that is the easiest to make and the most practical to use has a parallelepiped shape. When this type of splitter is inserted in a beam, the input wave front also appears at the output, but there are one or several additional phase shifts due to at least two different optical paths (Figure 3).

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For some applications of the invention, it may be necessary to use a non-parallelepiped shaped splitter in order to adapt the configuration of this splitter to the wave front of the beam for which the phase is to be

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shifted. For example, it may be necessary to make a phase change without changing the propagation characteristics of a non-parallel beam in which the splitter is inserted; for example (Figure 5) a splitter 9 delimited by two coaxial cylindrical faces 11 and 13 can be made; due to the optical path transition symbolized by line 15, a splitter of this type placed in a beam that converges on the axis common to the faces, induces a phase shift on the beam as shown in the example in Figure 3.

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A phase change may also be necessary with a change in the beam propagation characteristics. For example, this could be done using a lens that could be considered as a non-parallelepiped shaped splitter. The phase change is then inserted using the same principle as above. A cylindrical lens 16 can be seen in the example in Figure 6, that focuses a beam while applying a phase skip to it due to the transition of the optical path symbolized by line 17.

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The phase skip in the splitter can be obtained by changing its thickness. This can be done by etching one or several parts of the splitter or by depositing one or several layers on one or several parts of the splitter. For example, considering a splitter with two areas with thicknesses e_1 and e_2 respectively, the wave front is deformed after passing through the splitter due to the phase shift $\Delta\Phi = (2\pi / \lambda)\ (n - 1)\ (e_2 - e_1)$ where n is the index of the material from which the splitter is made and λ is the wavelength of the beam that passes through it.

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Thus, a splitter with a thickness e_2 can be used that is inserted in a certain beam thickness perpendicular to the wave planes of the beam (hence $e_1 = 0$).

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The wave propagation index in one or several parts of the splitter can also be modified to induce one or several optical path changes and therefore one or several phase skips. For example, consider a splitter with thickness e and index n. If the index becomes n' for a thickness e' as shown in Figure 7, the result will be $e'(n'-n) = (2k + 1)\lambda / 2$ (where k is an integer number). However, when the splitter is inclined (in order to adjust the phase shift), the two beams do not "see" the same index and therefore will be deviated differently. Therefore, a phase splitter with an index change at normal incidence should be used.

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In the case of a splitter with a thickness change, different phase shift values can be obtained by changing the inclination angle θ of the splitter with respect to the beam without inducing any angular separation. The inclination or rotation may be made about an axis A (Figure 8) parallel to the edges of the step that delimits the phase skip, or about an axis B perpendicular to the edges of the step and in a plane parallel to the two faces of the splitter.

The phase shift can be written as follows as a function of θ and θ' where $\theta' = \arcsin\left(\frac{\sin\theta}{n}\right)$, where $\Delta e = e_2 - e_1$ is the thickness of the deposit:

$$\Delta\Phi = \frac{2\pi}{\lambda}.\Delta e.\left[\frac{n}{\cos\theta^1} - \frac{1}{\cos\theta} + \sin\theta.(\tan\theta - \tan\theta^1)\right]$$

For example, molten silica can be deposited on an optical quality molten silica splitter (surface quality = $\lambda/10$) for use at λ = 244 nm. The order k is chosen to be 4 to obtain a variation of $\pm\pi$ of the initial value of the phase shift (equal to π) for an angular variation of ±45°. Therefore, the thickness $\Delta e = e_2 - e_1$ of the deposit will be:

$$(2k + 1)\ \frac{\lambda}{2(n-1)} = 2.15\ \mu m$$

where n = 1.51148 at 244 nm.

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Figure 9 shows a device 18 supporting a phase splitter 20 used to insert the phase splitter in a beam. This device comprises adjustment means that provide it with various degrees of freedom. The stacking order of these adjustment means is arbitrary. For the example shown, Figure 9 shows six adjustment means 19-1 to 19-6 corresponding to six degrees of freedom α, β, θ, y, z and x («y», «z» being the translations along the y and z axes perpendicular to each other; «x» being the translation along the x axis perpendicular to each of the y and z axes; and «α», «β» and «θ» being the rotations about axes parallel to y, z and x respectively). However, the support device may have more or less degrees of freedom depending on the configuration of the splitter and the wave front of the incident beam, and depending on the interferometric setup in which it is to be inserted (for example z is not essential).

In order to facilitate the use of the support device, one or several adjustment means are connected to one or several software controlled motors.

For example, a parallelepiped-shaped splitter can be adjusted based on five degrees of freedom:

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- α and β to keep the material change edges 22 vertical, that can also be achieved by construction,
- x to position the splitter in the beam,
- θ to adjust the phase shift value,
- y to adjust the position of the phase skip in the Bragg grating.

We will now consider how a device according to the invention can be inserted in an interference type setup. We decided to present Bragg grating writing setups made of optical fibers (for example fibers for which the core is doped with GeO_2), but the invention is also applicable to writing gratings in integrated optical guides.

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In the following examples, different configurations of interference setups are shown with the insertion of a phase splitter device in order to introduce a single phase change in a Bragg grating. Two writing configurations of a Bragg grating are considered. The first is an amplitude separation configuration in which the two beams are separated for energy but keep the same shape. The second is a wave front separation configuration.

We will distinguish two setups for the amplitude separation configuration. The first corresponds to the holographic setup described in document (10) which, like the other documents mentioned later, is mentioned at the end of this description.

The second setup corresponds to a setup with three mirrors (see document (1)). In both cases, a separating splitter 24 (Figure 10) divides a light beam 26 into two identical beams 28 and 30. An interferometric system with two or three mirrors (two mirrors 32 and 34 in the example in Figure 10) superposes these two beams 28 and 30 that form a given angle Ψ, at the fiber 36. The interferences thus created write the grating in the fiber by cylindrical focusing lenses 38 and 40. The phase splitter 42 needs to be placed in one of the two interfering beams.

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In general, the disadvantage of the amplitude separation setup is due to the fact that the phase splitter has to be adjusted each time that the Bragg wavelength is modified since the orientation of the insolation beam is modified. In order to overcome this disadvantage, the splitter support device (not shown) must be controlled along degrees of freedom y and θ (see above) by a program that takes account of the setup beam movements necessary for adjustment of the Bragg wavelength.

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We will now consider wave front separation configurations, and firstly an interferometric setup with a prism. Note that the method of separating the wave front has the advantage that the phase splitter can be placed immediately after the beam expansion system before the wave front separation. An important advantage of this configuration is that the phase shift can be adjusted by rotating the splitter independently of the Bragg wavelength adjustment that is obtained by rotating the interferometric system.

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The prism writing method (see document (8)) is diagrammatically illustrated in Figure 11 in which an extended beam 44 is "folded on itself" by reflection on a face of the prism 46. In Figure 11, the reference 48 shows a cylindrical lens. It can be seen that the determination of the Bragg wavelength fixed by the inclination of the two interfering beams, can be adjusted by rotating the prism, against which the fiber 36 is placed. If this rotation is made about an axis perpendicular to the plane of the Figure and passing through the phase skip projected in the optical fiber, then the phase splitter 42 placed on the trajectory of the beam 44 in front of lens 48, does not need to be adjusted for the different prism positions.

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A wave front separation method that uses a Lloyd mirror (see document (11)) and that is illustrated in Figure 12, can also be used. A second return mirror symmetric to the Lloyd mirror about the center of the grating, and a CCD camera type position system sensitive to ultraviolet radiation and particularly to the writing wavelength (244 nm in our case) is used to display and adjust the writing beams, in order to provide more flexibility in adjusting the parameters.

A Bragg grating can be written into an optical fiber 36 by photosensitivity, advantageously making use of an frequency doubled argon laser 50 that emits a beam 52 with a wavelength of 244 nm, but other laser lines or even other lasers can also be used such as a KrF excimer laser or a neodymium doped YAG laser quadrupled in frequency.

The beam 52 is reflected by a series of mirrors such as mirror 54 and is then filtered and stretched by two telescopes, one spherical 56 and the other cylindrical 58 after passing through a periscope 60. The beam then passes through the phase splitter 42 placed on a support device 61 with several degrees of freedom. The beam, in which the wave front has been modified, is then focused by a cylindrical lens 62 in the core of the optical fiber 36. This fiber is located at the edge of the Lloyd mirror 64 that "folds" the two half-parts of the beam on themselves. Thus, the beam creates interferences focused in the fiber core over a length defined by the position of a cover 66. The cylindrical lens 62 and mirror 64 are placed on two rotation plates 63 and 65 respectively that can advantageously be motor-driven. Their orientation with respect to the beam defines the Bragg wavelength of the written grating. Note that the polarization of the laser beam is vertical (normal to the work plane).

A second mirror 68, placed symmetrically with respect to the center of the grating to be written, is used to display the distribution of intensity writing the grating. When the beam is focused slightly above the fiber, the second mirror returns a divergent beam similar to the beam that is propagated without reflection. These two parts of the beam are collimated by a cylindrical lens acting as the inverse of the lens 62 and are finally analyzed by a CCD camera 72 fitted with an objective 74 with an appropriate magnification.

The distribution of intensity in the plane of the CCD camera is characteristic of the envelope of the

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intensity distribution of the two half parts of the beam on the focusing line at the Lloyd mirror. Provided that the Fresnel diffraction effect between the grating and the camera can be corrected, this distribution can be used to determine the envelope of the beam intensity generating the Bragg grating. This setup property is used to adjust the position in the grating of the phase skip(s) (using the y degree of freedom), with optimum control due to the diffraction pattern generated by edge effects related to each thickness change in the phase splitter. When this adjustment has been made, the laser beam is focused in the optical fiber and writing the required Bragg grating can begin.

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We will now describe several applications of the invention for making Bragg grating devices.

A. The invention is applicable to the manufacture of phase skip Bragg gratings, at high spectral selectivity.

One of the improvements to the Bragg grating was to demonstrate a thin secondary transmission band, called the second transmission peak, in the reflected wavelength. Thus, the corresponding component, usually called a "phase skip Bragg grating", transmits a very specific wavelength from the initial spectrum of the guided wave in the reflected wavelength band (see Figure 13, to be compared with Figure 1).

There are many applications of this type of component in the various fields in which conventional Bragg gratings are used. It can be used for the manufacture of matchable lasers and laser diodes. It

can also be used in wavelength multiplexing and demultiplexing systems. Furthermore its very good wavelength selectivity makes it a more efficient transducer than conventional gratings. Finally, it forms a new component with its own characteristics that can easily be applied to solve many guided optics problems.

Several techniques have been developed to make this second transmission peak. All use the basic principle of a phase mismatch between two parts of a conventional Bragg grating. The guided wave 76 (Figure 14) that passes through a conventional Bragg grating 78 is reflected around the Bragg wavelength λ_{Bragg} since the modulation with period Λ that forms the grating makes a distributed reflection of the wave in phase around a resonance wavelength (in other words λ_{Bragg}) given by the relation $\lambda_{Bragg} = 2n.\Lambda$. A constructive interference phenomenon occurs throughout the length of the grating.

If a phase change is formed at the center of this type of conventional grating (n = effective mode index) the two halves of this grating interfere with each other destructively. The wavelength thus selected can no longer be reflected and is transmitted in the second peak. If the transmission is to take place at λ_{Bragg}, the two parts that interfere must "see" a total phase shift $\Delta\varphi$ equal to π (modulo 2π), which is the reason for the name "π phase skip Bragg grating".

The desired effect can be obtained if a resonant cavity 80 with a length such that the total induced phase shift is equal to π, is inserted in the middle of

the grating. Thus, we usually consider a phase skip of $\pi/2$, the phase shift due to passing through the cavity. We can consider a phase shift of $\lambda/4$, the value of the optical width of the cavity necessary to produce a forward-return phase shift equal to π.

We can also form a phase change grating. In this case, the phase mismatch is no longer due to a cavity but is due to a change in the phase of the periodic modulation that forms the grating. The result is then identical; a transmission peak appears at the Bragg wavelength for two modulations with a phase difference π with respect to each other. The form of the index modulation for the case of an amplitude index modulation Δn_0 with period Λ along an abscissa z and for a grating of length L, and a phase shift at the center equal to $\Delta\Phi$, is as follows:

$$\Delta n(z) = \Delta n_0.\cos\left(\frac{2\pi}{\Lambda}z+\Phi_1\right) \text{ for } 0 < z < \frac{L}{2}$$

$$\Delta n(z) = \Delta n_0.\cos\left(\frac{2\pi}{\Lambda}z+\Phi_1+\Delta\Phi\right) \text{ for } \frac{L}{2} < z < L$$

We will now study the spectral response of a phase skip Bragg grating. We will consider the case of a periodic modulation of the propagation index in the core of an optical fiber. The index modulation is represented by the following formula:

$$\Delta n(z) = \Delta n_0.\cos\left(\frac{2\pi}{\Lambda}z+\Phi(z)\right)$$

where $\Phi(z) = 0$ for $0 < z < z_t$ and $\Phi(z) = \Delta\Phi$ for $z_t < z < z_f$.

We will now consider the propagation and counter-propagation modes A^+ and A^-. The index modulation will

act as a disturbance causing coupling between the two modes. This will be represented by the following coupling equations:

$$\frac{dA^-}{dz} = j\Omega A^+ e^{j[2\Delta\beta.z+\Phi(z)]}$$

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$$\frac{dA^+}{dz} = j\Omega A^- e^{j[2\Delta\beta.z+\Phi(z)]}$$

Ω is the coupling coefficient at wavelength λ in a fiber with a confinement factor η (proportion of energy guided in the core and interacting with the grating):

$$\Omega = \frac{\pi\Delta n_0}{\lambda}\eta$$

$\Delta\beta$ represents the phase match between the propagation wavelength and the resonance wavelength (where n is the propagation index): $\Delta\beta = \frac{2\pi}{\Lambda} - \frac{4\pi}{\lambda}n$.

We will now consider the two conventional Bragg gratings adjacent to the abscissa $z = z_t$ with a phase skip $\Delta\Phi$. The system of equations in the two areas is solved with the boundary conditions defined in Figure 15:

$$A_1^+(0) = 1 \qquad A_2^-(z_f) = 0$$

$$A_1^+(z_t) = A^+_2(z_t) \qquad A_1^-(z_t) = A_2^-(z_t)$$

The value of $|A_2^+(z_f)|^2$ then gives the expression for the spectral transmission of the grating as a function of the wavelength, the index modulation Δn_0, the phase shift $\Delta\Phi$ and the lengths of the two areas $l = z_t$ and $l' = z_f - z_t$ respectively. It is demonstrated that the transmission of a single phase skip grating can be written:

$$T(\lambda,\ \Delta n_0,\ \Delta\Phi,\ l,\ l') = \frac{\gamma^4}{\Gamma^2 + (C_1 - \Gamma)[C_1 - \Gamma(1 - 2\cos(\Delta\Phi))] + C_2(C_2 - 2\Gamma\sin(\Delta\Phi))}$$

where: $\gamma^2 = \Omega^2 - \Delta\beta^2$ $\quad L = l + l'$

$S = \sinh(\gamma.l).\sinh(\gamma.l')$ $\quad C_1 = \gamma^2\cosh(\gamma L)$

$\Gamma = \Omega^2 S$ $\quad C_2 = \Delta\beta\sinh(\gamma L)$

It can easily be checked that the typical transmission formula for a uniform Bragg grating is obtained for $\Delta\Phi = 0$.

If $\Delta\Phi = \pi$ and $l = l'$, the formula is simplified to give:

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$$T = \frac{\gamma^4}{\Delta\beta^2\left(\Delta\beta^2\cosh^2(\gamma L) + \gamma^2\sinh^2(\gamma L) - 2\Omega^2\cos(\gamma L) + \Omega^4\right)}$$

Note that if the resonant wavelength, $\Delta\beta = 0$ is considered, the result is $T = 1$ regardless of the values of Δn_0 and L.

If $\Delta\Phi = \pi$ and $l \neq l'$, the value of the transmission at the Bragg wavelength is no longer equal to one. The result is:

$$T(\lambda_{Bragg}) = \frac{1}{\cosh^2[\Omega(l - l')]}$$

Thus, the transverse displacement of the phase splitter in the writing beam makes it possible to precisely define the value of the filter transmission coefficient at λ_{Bragg}.

If $\Delta\Phi \neq \pi$, the position of the secondary peak in transmission is no longer matched to the Bragg wavelength.

Different methods are known for manufacturing phase skip gratings, and particularly the method that

uses phase change masks. The method used in document (4) is spatial frequency doubling lithography (SFDL): firstly a grating is formed on a mask using the electron beam emission system (EBES), and the Bragg grating is then written in the guide by SFDL. Document (7) describes the phase skip Bragg grating written using the phase mask method. The mask is composed of a grating with a phase skip in its modulation period, which is transmitted by photosensitivity in the fiber core and the value of the phase skip in the Bragg grating is fixed by the value of the phase skip in the mask grating. With this second known method, the parameters cannot be modified directly and therefore the cost of a specific and limited implementation is very high since a mask has to be created for each spectral position of the grating.

We will now mention the advantages of the invention for making these phase skip gratings in optical fibers (but the invention is also applicable to integrated optical guides):

1. Good manufacturing "flexibility": the adjustment of the transfer function of the phase skip grating in transmission, namely the transmission level and the spectral position of the peak, is adjusted simply and in a decorrelated manner. The first adjustment (transmission) is made by offsetting the splitter with respect to the insolation wave half-front (degree of freedom y) and the second adjustment (spectral position) is made by rotating the splitter with respect to the beam

(degree of freedom α or θ). The Bragg wavelength of the written grating is independent of the splitter. Therefore, the splitter can be used to produce the required spectrum at any position within the normal wavelength band for this type of application. This is the main advantage provided by the process according to the invention compared with the phase mask method. Furthermore, any type of grating can be written (for example a variable modulation pitch grating or an apodized grating) since the invention only influences the phase.

2. Control of the result; the different parameters are adjusted by moving the splitter (using rotation plates and translation plates, preferably motor-driven). Since these movements can be very precisely quantified, the instrument can give very good control of grating manufacture.
3. Reproducibility of the manufacturing process is just as good as for a conventional Bragg grating written by an interferometric setup since a phase skip grating is produced in a single step.
4. Ease of use: it is very easy to use the instrument, it simply needs to be placed in the writing beam and the adjustment settings are made by moving plates. In the same way as for the phase mask method, the grating is written

in a single step, which is also an important advantage compared with other methods.

5. Production cost: the cost of the apparatus is not very high since it is not expensive to manufacture a phase splitter by deposition, and it is relatively easy to install it on a moving plate. Since the apparatus is also capable of writing all possible wavelengths, it can also be considered as being very cost effective. It is also economically attractive since it can be used to make other components.

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Another advantage of this apparatus is related to its adaptation capabilities. It can thus be used to write Bragg phase skip gratings in optical fibers or in planar guides or even in semi-conductors. Since the splitter only influences the phase of the beam, modifications usually used for writing Bragg gratings (for example apodization of the spectral response in order to reduce secondary spectral lobes in the transmission spectrum) can be adapted to the writing process.

If several phase splitters are placed in the path of the beam, Bragg gratings with multiple phase skips can be written, the advantage of which has already been described (see document (13)).

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For example, a Bragg phase skip grating has been written with the following characteristics; grating length = 10 nm; insolation power = 10 mW; optical fiber type = hydrogenated SMF28; writing duration = 10 minutes. After writing, the spectrum was analyzed with a matchable source with a resolution of 1 pm. The

experimental plot agrees well with the theoretical plot obtained using the equations described above. The phase skip is determined by comparing the two plots.

B. The invention is also applicable to the manufacture of erasable Bragg gratings.

When writing a Bragg grating using an interferometric method like the methods described above, it is possible that the Bragg wavelength of the written grating is different from what is expected. This is due to the poor reproducibility of these methods (particularly due to uncertainty about knowledge of the real writing angle). It is possible that the characteristics of the written grating are not the same as were originally required, due to the lack of stability of the setup or due to a setting error or poor knowledge of the effective propagation index of the guide. In general, the fiber in which this grating is written must be sacrificed.

One elegant solution for solving this problem is to be able to erase gratings that do not have the originally expected characteristics. Thus, test gratings can be written in a fiber without altering its spectral properties. In this way, interferometric methods become more reproducible.

A Bragg grating written in a guide was considered. It can be represented by the following expression:

$$n(z) = n_0 + \Delta n_{aver} + \Delta n_0 . \cos\left(\frac{2.\pi}{\Lambda}.z\right)$$

Suppose that a grating is then written identical to the previous grating at the same position, except

for a phase change equal to π over the grating length. The result is then:

$$n(z)=n_0+\Delta n_{aver}+\Delta n_0.\cos\left(\frac{2.\pi}{\Lambda}.z\right)+\Delta n_{aver}-\Delta n_0.\cos\left(\frac{2.\pi}{\Lambda}.z\right)=n_0+2.\Delta n_{aver}$$

The modulation term has disappeared, and all that remains is an average increase in the index. If the transmission spectrum around the Bragg wavelength is observed, the filtering effect is no longer seen. The Bragg grating has been erased.

One possible practical solution would be to move the grating in translation by a half-period in order to rewrite a grating in phase opposition, but this would require the use of a translation plate with the precision of at least 0.1 micrometers (the interference pitch is usually about 0.5 µm). Furthermore, the translation could degrade the focusing setting in the core.

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~~The invention solves this problem in a very simple and inexpensive manner. The phase splitter is placed in the beam using the device with several degrees of freedom. The position of the phase skip is outside the grating such that the phase in the grating is constant. The grating is then written in the same way as if there had been no splitter. If the decision is made to erase the grating, then the device is ordered to translate the splitter to create a phase change of π over the entire grating. For example, for a Lloyd mirror grating, this is equivalent to placing the phase skip on the optical axis of the beam, to shift the two interfering parts out of phase by π. This then prolongs writing until the grating spectrum disappears.~~

The final effect is what could be called an opposite overwriting.

For example, a conventional Bragg grating with a length of 4 millimeters is written in an hydrogenated optical fiber (140×10^5 Pa for three weeks). At a given writing level, the device is moved in translation in order to over-write another grating identical to the first grating, in phase opposition. The reflection coefficient decreases after translation of the device to return to its initial value. The grating erase time is equal to the writing time, and a new grating can be written continuously once the previous grating has been completely erased.

We will now describe the advantage of the invention for making erasable gratings:

1. Good "flexibility": unlike the solution provided by translation, the setting in this case is independent of the value of the modulation pitch and therefore of the grating wavelength. Since only the phase is changed, this erasing principle can be applied to all sorts of gratings (for example chirped gratings) and phase skip gratings.
2. Control of the result: the phase change parameter is well-controlled due to the use of this apparatus. Very high precision is not necessary for translation of the splitter; 0.1 mm is sufficient. The grating can be erased with the required precision on the residual reflection value, provided that the variation of the spectrum can be monitored in real time.

3. Reproducibility: reproducibility is not a problem in this case. Erasing can be done reproducibly since the phase shift is controlled.
4. Ease of use: there are no difficulties in erasing, provided that the change in spectral characteristics of the grating can be monitored in real time, since all that is necessary is a translation control on the splitter support device and closing of the laser beam at the right time.

Note that, due to the invention, the writing bench can be calibrated regularly without modifying the transmission spectrum of the fiber used to write the test grating.

Furthermore, erasing the grating is a means of obtaining a low reflection coefficient at the end of writing and not at the beginning. Thus, the focusing adjustment in the core has already been made and does not disturb growth of the grating.

C. The invention is also applicable to the production of Fabry-Perot cavity Bragg gratings.

A Fabry-Perot interferometer comprises a cavity delimited by two mirrors with reflection coefficients R1 and R2. A matched resonance phenomenon occurs on the phase shift induced by the cavity when a light wave with wavelength λ penetrates into the cavity. When there are no losses in the two mirrors and $R1 = R2 = R$, the intensity at the output from the interferometer is in the following classical form:

$$I(\lambda) = \frac{1}{1+\frac{4R}{(1-R)^2}.\sin^2\left(\frac{2\pi}{\lambda}.n_{cavity}.e\right)}$$

n_{cavity} is the intra-cavity index assumed to be equal to one for the case of two mirrors in air and e is the width of the cavity. The response as a number of waves ($\sigma = 1/\lambda$) is a periodic function corresponding to a comb. The interval between two peaks (or a free spectral interval denoted ISL) is given by the relation:

$$\Delta\sigma = \frac{1}{2.n_{cavity}.e}$$

The thinness of the lines depends on the value of the reflection coefficient from the two mirrors and their height depends on the difference between the two reflection coefficients.

A Bragg grating may be considered like a mirror about its resonant wave length. It reflects a spectral band with a given reflection coefficient. If two Bragg gratings with the same period are put one after the other, then a Fabry-Perot cavity is created. In the example of application A, a single secondary peak was added. A series of peaks can be added into the band reflected by the complete set of the two gratings by adjusting the distance e between the two gratings.

The fact that a Bragg grating is not a plane reflector like a mirror, but is rather a reflector distributed over its entire length, implies that the free spectral interval of a Fabry-Perot cavity grating is not constant.

The cavity can be made by opposite overwriting. Consider a Bragg grating with an index modulation amplitude $\Delta n_0/2$ with a phase change of π at abscissa $z = z_1$. The total length of the initial grating is denoted L, the modulation period is denoted Λ, and the final average index variation is denoted Δn_{aver}. This grating can be represented by the following index change equation:

$$\Delta n_1(z) = \frac{\Delta n_{aver}}{2} + \frac{\Delta n_0}{2}.\cos(\frac{2\pi}{\Lambda}.z) \quad \text{for } 0 \le z \le z_1$$

$$\Delta n_1(z) = \frac{\Delta n_{aver}}{2} + \frac{\Delta n_0}{2}.\cos(\frac{2\pi}{\Lambda}.z) \quad \text{for } z_1 \le z \le L$$

Another grating identical to the first grating is considered but with a phase change at the abscissa z2 ($z_1 \le z_2$). Let Δn_2 (z) be the representative function. The index modulation that will be obtained from the sum of these two variations is written as follows, with the two parts of the grating in phase opposition canceling each other out:

$$\Delta n(z) = \Delta n_1(z) + \Delta n_2(z) = \Delta n_{aver} + \Delta n_0.\cos\left(\frac{2\pi}{\Lambda}.z\right)$$

$$\text{for } 0 \le z \le z_1$$

$$\Delta n(z) = \Delta n_1(z) + \Delta n_2(z) = \Delta n_{aver} \qquad \text{for } z_1 \le z \le z_2$$

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$$\Delta n(z) = \Delta n_1(z) + \Delta n_2(z) = \Delta n_{aver} + \Delta n_0.\cos\left(\frac{2\pi}{\Lambda}.z\right)$$

$$\text{for } z_2 \le z \le L$$

If $z_1 = \frac{L-e}{2}$ and $z_2 = \frac{L+e}{2}$, the result will be a Bragg grating with a Fabry-Perot cavity.

Different methods are known for manufacturing a Fabry-Perot cavity Bragg grating, particularly as

described in document (9) in which it is achieved by writing two successive Bragg gratings at a spacing equal to the length of the cavity. The match on the spectral interval and on the position of the peaks is obtained by uniform insolation of the cavity that modifies the value of the propagation index in this area. With this method, the Fabry-Perot cavity grating has to be written in three steps. In particular, it is necessary to write two successive gratings, which increases the manufacturing difficulty.

The invention can be used to make a Fabry-Perot cavity grating by opposite overwriting. The invention is a means of positioning a phase skip of π in a grating, an apparatus according to the invention needs to be placed at a certain abscissa during a time t_1 and then at another abscissa during a time t_2 in order to make a Fabry-Perot cavity. $\Delta n(t)$ needs to be qualified during the experimental protocol for making the Fabry-Perot cavity Bragg grating, in order to determine the total writing time.

The first step is to determine the experimental conditions for the Fabry-Perot cavity grating to be written; the lengths l_1 and l_2 of the two Bragg gratings and their reflection coefficients R_1 and R_2, the length of cavity e, the fiber type and the insolation power. All these parameters are used to plot the spectrum using a matrix method (see document (12)) and thus to predict the shape of the spectral response of the Fabry-Perot cavity grating. The length of the cavity and the value of the average index change

need to be known to determine the free spectral interval. The following procedure can be used:

Δn_0 is deduced using the following relation:

$$\Delta n_0 = \frac{\lambda_{Bragg}}{\pi.\eta.l_i}.\arg\tanh\left(\sqrt{R_i}\right) \text{ where } i = 1,\ 2$$

where η is the confinement factor for the wave guided in the core. The total length L of the grating is given by $L = l_1 + e + l_2$. There is a reflection coefficient R corresponding to this length L and this index modulation, given by:

$$R = \tanh\left(\frac{\pi.\Delta n_0}{\lambda_{Bragg}}.\eta.L\right)$$

Therefore, a grating with length L is written to obtain a reflection coefficient R. Let the measured insolation time be t_{total}. During this writing, the Bragg wavelength was offset by $\Delta\lambda_{Bragg}$ corresponding to the increase in the value of the average index Δn_{aver}:

$$\Delta n_{aver} = \frac{\Delta\lambda_{Bragg}}{2.\Lambda}$$

The free spectral interval can thus be determined:

$$\Delta\sigma = \frac{1}{2.(n_0 + \Delta n_{aver}).e}$$

There are two possibilities if the value of the ISL is not suitable; either e can be changed and writing can be repeated to determine the new value of t_{total}, or the process can be continued and writing can be finished by a uniform insolation of the cavity which will have the effect of increasing the average index.

The insolation times for the two gratings with opposite phases are equal: $t_1 = t_2 = \dfrac{t_{total}}{2}$.

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The first two test gratings can be erased using the method described above. We can now write the Fabry-Perot cavity grating. The phase skip is placed at a distance l_1 from the edge of the grating using an apparatus conform with the invention, a grating is written for a time t_1, and the splitter is then moved by translation using its support device over a distance e, and writing is prolonged by a time t_2. The Fabry-Perot cavity Bragg grating is written.

We will describe the advantages of the invention for making this type of Bragg grating.

1. Manufacturing "flexibility": any Bragg wavelength can be written, in the same way as for the phase skip grating. The cavity length and the length of the two gratings is limited by the maximum size of a Bragg grating that can be written by the interferometric setup used. It is not limited by the apparatus, which includes a means of adjusting the length of the cavity with the precision possible by the adjustment in y. The reflection coefficients of these two gratings can be chosen by varying the total writing duration and the relative length of the two gratings. Therefore, it can be seen that most of the parameters are accessible with good "flexibility".
2. Reproducibility: there is no reproducibility problem related to the value of the wavelength of the two Bragg gratings since they have the same period. This is an advantage compared with known methods.

D. The invention is also applicable to the manufacture of a Bragg grating with a particular index modulation envelope.

The equation for a non-uniform Bragg grating can be written in the following form:

$$\Delta n(z) = \Delta n_{aver}(z) + \Delta n_{mod}(z) . \cos\left(\frac{2.\pi}{\Lambda}.z\right)$$

$\Delta n_{avery}(z)$ is the average index distribution (as a function of the abscissa z), $\Delta n_{mod}(z)$ is the index modulation envelope of the Bragg grating, and Λ is the modulation period;

More sophisticated components can be obtained by making non-uniform gratings. For example, it is often desirable to apodize the gratings. The transmission spectrum of an apodized grating includes very small bounce on each side of the central peak, making it a particularly attractive component for all types of applications.

We will now consider the principle of dynamic phase shifted overwriting; we will use the basic principle presented in application examples B and C (successive writing of two gratings with parts in phase opposition), except for the difference that overwriting is done for variable times and for variable phase skip positions and values. Analytically, this is equivalent to considering a grating growth defined by the following relation:

$$\Delta n(z, T) = \int_0^T \left[a(z,t) + b(z,t) . \cos\left(\frac{2.\pi}{\Lambda}. z + \Phi(z,t)\right)\right] dt$$

where $a(z,t) = \frac{\partial \Delta naver}{\partial t}(z,t)$ and

$$b(z,t) = \frac{\partial \Delta n_{mod}}{\partial t}(z,t)$$

a(z,t) characterizes the growth kinetics of the average index change in the grating, depending on a large number of parameters (for example the insolation power and fiber type) and can be determined by studying the variation of the Bragg wavelength while writing a test grating.

b(z,t) characterizes the growth kinetics of the index modulation envelope in the grating, and depends on many parameters and can be determined by studying the variation of the maximum reflection coefficient while writing a test grating.

$\Phi(z,t)$ is the function defined by the position and inclination of the splitter(s). This is a step function.

The variation of the average index cannot be modified using the invention. Therefore, we will only use the value of the index modulation:

$$\Delta n_{per.}(z,T) = \int_0^T \left[b(z,t).\cos\left(\frac{2.\pi}{\Lambda}.z + \Phi(z,t)\right)\right].dt$$

We can write:

$$\Delta n_{per.}(z,T) = \left\{\int_0^T [b(z,t).\cos(\Phi(z,t)].dt\right\}.\cos\left(\frac{2.\pi}{\Lambda}.z\right)$$

$$- \left\{\int_0^T [b(z,t).\sin(\Phi(z,t)].dt\right\}.\sin\left(\frac{2.\pi}{\Lambda}.z\right)$$

It can be seen that the modulation term is the sum of two amplitude modulations determined by the function

$\Phi(z,t)$. A special application case is given when the value of Φ is 0 or π. Firstly, we will consider a dynamic opposite overwriting with a single skip. We can define:

$\Phi(z,t) = \pi$ if $0 \le z \le z_\pi(t)$

$\Phi(z,t) = 0$ if $z_\pi(t) \le z \le L$ (L = length of the Bragg grating).

The $z_\pi(t)$ function defines the phase skip movement. The grating growth at abscissa z is a function of the phase shifted modulation time ($t_\pi(z)$) or the unshifted modulation time ($t_0(z)$) applied to the elementary part of the grating. The total writing time is denoted T. The final index modulation amplitude of the grating at abscissa z is denoted $\Delta n^T{}_{mod}{}^{(z)}$. We can write:

$$\Delta n^T{}_{mod}(z) = \left| \int_0^{t_0(z)} b(z,t).dt - \int_{t_0(z)}^{T} b(z,t-t_0(z)).dt \right|$$

The standard modulation envelope A(z), is defined as $\Delta n^T_{mod}(z) = \Delta n_0 x A(z)$. In general, the minimum value of this function is denoted A_0. A(z) is the function to be obtained in the grating. This cannot be done unless the growth dynamics of the index modulation are known. It will be assumed that this growth function is known and is independent of the abscissa in the grating. We will set:

$$\Delta n_{mod}(t_0) = \int_0^{t_0} b(t).dt$$

hence:

$$A(z) = \left|\frac{\Delta n_{mod}(T - t_0(z))}{\Delta n_0} - \frac{\Delta n_{mod}(t_0(z))}{\Delta n_0}\right|$$

Thus, there are two possible cases that correspond to two choices of the phase skip movement (move then rest or rest then move). These two movements give exactly the same result.

We will now consider the case:

$$A(z) = \frac{\Delta n_{mod}(T - t_0(z))}{\Delta n_0} - \frac{\Delta n_{mod}(t_0(z))}{\Delta n_0}$$

This choice defines the time interval of the phase skip movement:

$A(z) \geq A_0$ implies $\Delta n_{mod}(t_0(z)) \leq \Delta n_{mod}(T-t_0(z)) - \Delta n_0 x A_0$ which implies $t_0(z) \leq t_{sup}$

$A(z) \geq 1$ implies $\Delta n_{mod}(t_0(z)) \geq \Delta n_{mod}(T-t_0(z)) - \Delta n_0$ which implies $t_0(z) \leq t_{inf}$

We can deduce:

$z_\pi(t) = A^{-1}(1)$ for $0 \leq t \leq t_{inf}$

$z_\pi(t) = A^{-1}\left[\frac{\Delta n_{mod}(T-1)}{\Delta n_0} - \frac{\Delta n_{mod}(t)}{\Delta n_0}\right]$ for $t_{inf} \leq t \leq t_{sup}$

$z_\pi(t) = A^{-1}(A_0)$ for $t_{sup} \leq t \leq T$.

Therefore, we can see that making an index modulation according to function A(z) in the case of a method with dynamic opposite overwriting with a single skip is only possible if A(z) is a reversible function.

If A(z) is not defined over a bijection interval, another method has to be applied. This interval has to be broken down into bijection parts. The number of phase skips to be placed in the beam is then equal to the number of the bijection intervals.

Let N be the number of bijections, and let i be the number of bijection interval of A(z) $[z_{i-1}; z_i]$.

We can define Δn_0^i: $\Delta n_0^i = \max(\Delta n_0.A(z))$ in $[z_{i-1};z_i]$ and $A_i(z)$ as an application of $[O; z_i-z_{i-1}]$ in $[O; 1]$ which associates $\frac{\Delta n_0}{\Delta n_0^i} . A(z_{i-1} + Z)$ with z.

This problem is solved in the same way as in the case of a single skip. This is done by determining the movement of N phase skips by applying the formulas to series of functions $Z_\pi^i(t)$ defined with respect to each origin z_{i-1}. Therefore, regardless of the shape of A(z), the dynamic opposite overwriting method with multiple skips can be used to produce the corresponding grating.

We will now consider the production of a particular index modulation envelope according to the invention. The y translation of the splitter support device can be used to position the phase skip at any place in the grating. Therefore, a software controlled motor can control the movement $z_n(t)$ and thus induce a modification to the grating index modulation envelope.

If the function A(z) is not defined over a bijection interval, it is possible to place a series of devices provided with splitters in sequence to make the modification using the multiple skips method. In the same way as for a single support device, the various motors can be controlled to make the component. This production requires precise knowledge of the grating growth function, $\Delta n_{mod}(t)$. This knowledge can be obtained by studying a test grating for which the

variation of the reflection factor is measured with respect to time. This measurement must be made at the same power as the power that will be used later to make a grating in the form A(z). The required function is deduced using the following relation:

$$\Delta n_{mod}(t) = \frac{\lambda_{Bragg}}{\pi.\eta.L}.\arg\tanh\left(\sqrt{R(t)}\right)$$

(see above for writing a Fabry-Perot cavity Bragg grating).

More simply, the function A(z) may be approximated by assuming the growth of the modulation index to be linear with respect to time. In this case, the formulation of the equations is very much facilitated.

We will now describe the advantage of the invention for making a Bragg grating with a particular index modulation envelope.

1. Manufacturing "flexibility": a Bragg grating with a constant or chirped spatial period can be written at any Bragg wavelength and any shape of index modulation or average index envelope, provided that an appropriate number of support devices equipped with phase splitters are placed.

2. Ease of use: it is easy to produce the grating. All that is necessary is to measure the growth function of a grating at a given power, and then to invert the function A(z) to be produced. Each splitter support device, with its control software installed on it, then manages displacement of the corresponding splitter.

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Note that the growth function of the modulation index with respect to time may be determined experimentally.

We will now give a few example applications.

The case of a linear approximation is considered, to describe them easily $\Delta n_{mod}(t) = a.t$.

a) We can attempt to write a grating with a linear modulation envelope of the type shown in Figure 16. The phase skip movement for a linear approximation is defined as follows:

$$Z\pi(t) - \frac{2.L}{T}.t \text{ for } 0 \leq t \leq \frac{T}{2} \text{ and}$$

$$z_{\pi}(t) = L \text{ for } \frac{T}{2} \leq t \leq T.$$

b) An attempt can be made to apodize a Bragg grating. A gaussian envelope is chosen:

$$A(z) = \exp[-(z-L/2)^2/(L/N)^2]$$

The shape of the grating when N = 4 is as shown in Figure 17. This shape is used to apodize the grating, or more precisely its spectral response. The secondary lobes in the reflection spectrum for this grating are smaller than with a conventional grating.

In the example considered, A(z) is not defined over a bijection interval. Therefore, two functions are defined:

Interval 1: [0;L/2]:

$A_1(z) = \exp[-(z-L/2)^2/(L/N)^2]$ for z within [0; L/2]

$$A_0^1 = 0$$

$$An_0^1 = \Delta n_{mod}(T)$$

Interval 2: [L/2;L]

$A_1(z) = \exp[-(z^2/L/N^2]$ for z within [0; L/2]

$$A_0^2 = 0$$

$$An_0^2 = \Delta n_{mod}(T)$$

We can deduce the movement of the two phase skips:

Interval 1:

$$z_\pi^1(t) = \frac{L}{2}.\left[1 - \frac{2}{N}.\sqrt{\ln\left(\frac{T}{T-2.t}\right)}\right] \qquad \text{for } 0 \le t < \frac{T}{2}$$

$$z_\pi^1(t) = 0 \qquad \text{for } \frac{T}{2} \le t \le T$$

Interval 2:

$$z_\pi^2(t) = \frac{L}{2}.\left[1 - \frac{2}{N}.\sqrt{\ln\left(\frac{T}{T-2.t}\right)}\right] \qquad \text{for } 0 \le t < \frac{T}{2}$$

$$z_\pi^2(t) = L \qquad \text{for } \frac{T}{2} \le t \le T$$

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